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Electrical spin-injection into Silicon and Spin FET

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Jagadeesh S. Moodera

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The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
In this seedling proposal funded by DARPA the project formed the PhD thesis of the graduate student Marc van VeenHuizen of Physics Dept (MIT), who successfully defended his PhD thesis in December 2009. He is now a research engineer at Intel Semiconductor Company.
The aim of the project was to explore a tunneling emitter bipolar transistor as a possible spin injector into silicon, and we have succeeded in that goal. The transistor has a metallic emitter that as a spin-injector will be a

15. SUBJECT TERMS
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a. REPORT	b. ABSTRACT	c. THIS PAGE			Jagadeesh Moodera
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Report Title

Electrical spin-injection into Silicon and Spin FET

ABSTRACT

In this seedling proposal funded by DARPA the project formed the PhD thesis of the graduate student Marc van VeenHuizen of Physics Dept (MIT), who successfully defended his PhD thesis in December 2009. He is now a research engineer at Intel Semiconductor Company. The aim of the project was to explore a tunneling emitter bipolar transistor as a possible spin injector into silicon, and we have succeeded in that goal. The transistor has a metallic emitter that as a spin-injector will be a ferromagnet. Spin-polarized electrons from the ferromagnet tunnel directly into the conduction band of the base of the transistor and are subsequently swept into the collector. The tunneling emitter bipolar transistor as a spin-injector allows for large spin-polarized currents and naturally overcomes the conductivity mismatch and Schottky barrier formation. In this work, the various aspects of the transistor were analyzed. The transfer of spin-polarization across the base-collector junction was simulated. The oxide MgO was considered as a tunnel barrier for the transistor and thoroughly investigated.
Significant additional knowledge resulted in this project. Two journal articles have been published from this work in addition to two international conference presentations and a PhD thesis. Two more articles are under preparation

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List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. “Epitaxial growth of MgO and Fe/MgO/Fe magnetic tunnel junctions on (100)-Si by molecular beam epitaxy”, G. X. Miao, J. Y. Chang, M. J. van Veenhuizen, K. Thiel, M. Seibt, G. Eilers, M. Münzenberg, and J. S. Moodera, Appl. Phys. Lett. 93, 142511 (2008)

2. “Observation of negative differential transconductance in tunneling emitter bipolar transistors”, M. van Veenhuizen, N. Locatelli, J. Y Chang, and J. S. Moodera. Appl. Phys. Lett., 95:072102, (2009)

Number of Papers published in peer-reviewed journals: 2.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

N/A

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Two talks given at American Physical Society March meetings and Magnetism and Magnetic Materials Conference by Marc van VeenHuizen.

PhD thesis of Marc van Veenhuizen Dec 2009 (unpublished and available at MIT library)

Number of Presentations: 2.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

PhD thesis presentation

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 1

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Two manuscripts are under preparation for submission to Physical Review B journal

Number of Manuscripts: 2.00

Patents Submitted

Patents Awarded

Graduate Students

NAME	PERCENT_SUPPORTED
Marc van VeenHuizen	0.70
FTE Equivalent:	**0.70**
Total Number:	**1**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Jagadeesh S. Moodera	0.08	No
FTE Equivalent:	**0.08**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
Nicholas Locatelli	0.00
FTE Equivalent:	**0.00**
Total Number:	**1**

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
Marc van VeenHuizen

Total Number: **1**

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Proposal Number: 54398-MS-DRP (W911NF-08-1-0087)

Electrical spin-injection into Silicon and Spin FET

PI: Jagadeesh S. Moodera, MIT

In this seedling proposal funded by DARPA the project formed the PhD thesis of the graduate student Marc van VeenHuizen of Physics Dept (MIT). He successfully defended his PhD thesis in December 2009 and is now employed as a research engineer at Intel Semiconductor Company.

The aim of the project was to explore a tunneling emitter bipolar transistor as a possible spin injector into silicon, and we have succeeded in that goal. The transistor has a metallic emitter that as a spin-injector will be a ferromagnet. Spin-polarized electrons from the ferromagnet tunnel directly into the conduction band of the base of the transistor and are subsequently swept into the collector. The tunneling emitter bipolar transistor as a spin-injector allows for large spin-polarized currents and naturally overcomes the conductivity mismatch and Schottky barrier formation. In this work, the various aspects of the transistor were analyzed. The transfer of spin-polarization across the base-collector junction was simulated. The oxide MgO was considered as a tunnel barrier for the transistor and thoroughly investigated.

Significant additional knowledge resulted in this project. For example, with preliminary investigation electron spin resonance is proposed as a measurement technique to probe the spin-polarization injected into the collector. Spin-orbit coupling induced spin-interference of ring-structures is proposed as another approach for a spin-detector. Also, an IV fitting program that can extract the relative importance of the tunnel and Schottky barrier is discussed and employed to fit the base-emitter IV characteristics of the transistor. All these aspects as well as the development of several fabrication and experimental tools is described in the PhD thesis (publicly available from MIT library). The fabrication of the transistors and the importance of the tunnel barrier for the device operation is fully analyzed and discussed in the thesis.

The important observation of negative differential transconductance in the transistor and the interfacial properties of MgO on Si are described separately in detail below. Two journal articles have been published from this work in addition to two international conference presentations and a PhD thesis. Two more articles are under preparation for submission to Physical Review B. Overall the results of our novel approach discovered under this DARPA grant showing large emitter current and large transistor gain are excellent for the future development of spin field effect transistors. This certainly needs to be pursued and taken to the next level of actually detecting the injected spin polarized current using these bipolar transistors and creating an efficient spin FET.

Our subcontractors (Prof. Y. Hong at UCLA) provided the Si 2 Deg structures for device fabrication. The fabrication of Si bipolar transistor devices was extremely expensive, and along with their characterization used up most of the funds. Part of Marc van VeenHuizen’s research assistantship was paid from this grant.

1. "Observation of negative differential transconductance in tunneling emitter bipolar transistors"

In our approach to develop spin polarized source emitter for spin injection into Si studies we observed for the first time negative differential transconductance (NDTC) of Fe/MgO/silicon tunneling emitter *NPN* bipolar transistors. Device simulations revealed that the NDTC was the consequence of an inversion layer at the tunneling-oxide/*P*-silicon interface for low base voltages. Electrons travel laterally through the inversion layer into the base and give rise to an increase in collector current. The NDTC results from the recombination of those electrons at the interface between emitter and base contact which was dependent on the base voltage. For larger base voltages, the inversion layer disappeared marking the onset of normal bipolar transistor behavior. This work is published recently (Marc J. van Veenhuizen, Nicolas Locatelli, Jagadeesh Moodera and Joonyeon Chang, Appl. Phys. Lett. **95**, 072102 (2009))

Devices for the above studies were made from a low-doped *N*-type silicon 100 wafer on top of which was grown a 10μ thick *P*-type epilayer. The epilayer was partly thinned down using reactive ion etching etching gas SF_6 to various widths ranging anywhere from 1–5 μm. The backside contact was made with deposited Al, which formed the collector contact. Then the base contact was defined using photolithography and Al deposition. Finally, the emitter was fabricated with another photolithographic step followed by e-beam evaporation of MgO/Fe in our UHV system.

Negative differential conductance (NDC), which saw the limelight with the realization of the Esaki tunneling diode, had been predicted and observed to occur in a range of electronics devices. The fundamental origin is the appearance of bias dependent states into which charge carriers can tunnel. Much attention has been devoted to this phenomenon because of the promise it holds to realize high-frequency oscillators. Our observation of NDC is in the collector current of a tunneling emitter bipolar transistor, i.e., negative differential transconductance NDTC. Gate controlled NDC had been observed in tunnel transistors but never before in the transconductance of bipolar transistors, although theoretical studies of these kind of devices existed. Our measurement and simulation results are relevant as well for other NDC geometries such as FET style tunnel transistors since they offer crucial insight into how the geometry and charge distribution may determine the ultimate performance of such devices. Moreover, the implementation of the collector contact in our geometry may itself be used for device applications.

2. "Epitaxial growth of MgO and Fe/MgO on (100)Si by molecular beam epitaxy for spin polarized current emitter"

Epitaxial growth of MgO barrier on Si is of technological importance due to the symmetry filtering effect of the MgO barrier in conjunction with bcc-ferromagnets thereby giving rise to huge spin polarized current. We studied the epitaxial growth of MgO on (100)Si by molecular beam epitaxy. MgO matches Si with 4:3 cell ratio, which renders Fe to be 45° rotated relative to Si, in sharp contrast to the direct epitaxial growth of Fe on Si. Extensive transport and

transmission electron microscopy studies revealed details of the interface and the quality of the epitaxial MgO. The compressive strains from Si led to the formation of small angle grain boundaries in MgO below 5 nm, and also affected the transport characteristics of Fe/MgO/Fe magnetic tunnel junctions formed on top. This work is published a year ago (G. X. Miao, J. Y. Chang, M. J. van Veenhuizen, K. Thiel, M. Seibt, G. Eilers, M. Münzenberg, and J. S. Moodera, Applied Physics Letters **93**, 142511 (2008)). Thus our work shows that Fe/MgO(100) can be grown epitaxially on silicon by ebeam evaporation. Growth conditions require that the substrate be heated to 300C during growth which may complicate device fabrication. The MgO is under tensile strain, and if the MgO thickness is increased above 5 nm, it starts to relax introducing dislocations. It is yet to be seen whether the Fe/MgO on top of silicon acts as a spin-filter, considering the fact that the conduction band minimum of silicon is far away from the Γ-point.

Publications and presentations:

“Epitaxial growth of MgO and Fe/MgO/Fe magnetic tunnel junctions on (100)-Si by molecular beam epitaxy”, G. X. Miao, J. Y. Chang, M. J. van Veenhuizen, K. Thiel, M. Seibt, G. Eilers, M. Münzenberg, and J. S. Moodera, *Appl. Phys. Lett.* 93, 142511 (2008)

“Observation of negative differential transconductance in tunneling emitter bipolar transistors”, M. van Veenhuizen, N. Locatelli, J. Y Chang, and J. S. Moodera. *Appl. Phys. Lett.*, 95:072102, (2009)

Two talks given at American Physical Society March meetings and Magnetism and Magnetic Materials Conference by Marc van VeenHuizen.

PhD thesis of Marc van Veenhuizen Dec 2009 (unpublished and available at MIT library)

Personnel:

PI spent about a month’s equivalent of effort. The PhD student van VeenHuizen worked on this project full time (although part of his RA also was contributed by another KIST-MIT project which had interest in the outcome of this project). At UCLA a MS student was involved in the growth of samples.